National Defence / Défense nationale

COVERAGE STUDIES FOR SPACED-BASED RADAR

by

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 90-18

PCN
041LF

August 1990
Ottawa

91-01785/

Abstract

The coverage for air surveillance available with constellations of space-based radar satellites was simulated. The coverage was modelled as an annulus, defined by the grazing-angle limits of 3° and 50°, moving over the earth. The number, altitude, and orbital inclination of the satellites were varied, and targets were placed at various latitudes. A constellation of seven satellites, at 1000 km altitude, and 80° inclination gave nearly continuous coverage at the pole. Equivalent coverage was obtained with fewer satellites at higher altitudes, and lower orbital inclination.

Résumé

La couverture pour surveillance aérospatiale disponible avec une constellation de satellites radar spatials fut simulée. La couverture fut modellée par un anneau, défini par les limites d'angle rasant 3° et 50°, passant au-dessus de la terre. Le nombre, l'altitude et l'inclination orbitale des satellites furent variés, et des cibles furent placées à des latitudes diverses. Une constellation de sept satellites, à une altitude de 1000 km, et à une inclination de 80° donnèrent une couverture pratiquement continue au Pôle. Une couverture équivalente fut obtenue avec moins de satellites à des altitudes plus hautes et à des inclinations orbitales plus basses.

Executive Summary

This report describes the opportunities for detection of aircraft by generic constellations of space-based radar (SBR) satellites. The results were obtained by simulation. The field of view of an SBR satellite was modelled as an annulus moving over the surface of the earth. The outer limit of the annulus was defined by a grazing angle of 3°, essentially the horizon, while the inner limit was defined by a grazing angle of 50°.

The following constellation parameters were varied:

- the number of satellites
- the altitude of the satellites
- the orbital inclination
- the phasing of the satellites in their orbits

Targets were placed at various latitudes to provide coverage data as a function of latitude. These data were presented as the percentage of time that a target was visible to at least one SBR satellite, and the length of time the target could not be observed by any satellite.

For a target at the pole the best constellation was not one with a polar inclination because the target spends time in the blind region between the grazing-angle limits (the nadir hole).

There is a trade-off between altitude and inclination. Constellations having the low altitude of 1000 km require high inclinations of about 80° for effective coverage at high latitudes. At higher altitudes, lower inclinations were advantageous.

Similarly, there is a trade-off between the altitude of the constellation and the number of satellites required. At high altitudes of 5000 km or more, continuous coverage at latitudes above 80° was achieved with a constellation of four satellites. At an altitude of 1000 km, seven satellites were required for nearly continuous coverage.

Since many constellations could provide adequate coverage, the choice of constellation would depend on cost and other factors not considered in this report. These factors include radar performance and vulnerability to counter-measures.

Good coverage at high latitudes can be achieved with a constellation of seven satellites in orbits of altitude 1000 km and inclination 80°, or if the satellites were placed in higher orbits, with fewer satellites at a lower inclination.

Coverage Studies for Space-Based Radar

Introduction

This report presents results that quantify the opportunities for detection of aircraft by generic constellations of space-based radar satellites.

Several previous studies have been published in this area [Lang 1982], [Brousseau 1983 a], [Brousseau 1983 b], [Rook 1983], [Rook et al. 1985], [Slinn et al. 1986], [Desmier 1988 a], [Desmier 1988 b]. The results obtained in this report were compared with those previously published, to give confidence in the accuracy of our simulations. In addition, the results of the previous work are extended to cases that were not considered, but could be of interest to Canada.

Lang [1982] described coverage studies intended to find good constellations for the *North American Tactical Warning Mission* (NATW), essentially the NORAD role, and for the *Integrated Tactical Surveillance System (ITSS)*. The maximum revisit time to a location of interest was taken as the measure of performance. The objective for the NATW mission was to minimize revisit times for northern latitudes, while for the ITSS mission global coverage was required. Constellations in circular orbits at altitudes of 900 and 5600 nmi (1667 and 10371 km) and constellations in elliptical orbits at 350 × 6560 nmi (648 × 12149 km) were studied. It was assumed that a target lying in an annular region between grazing angles of 3° and 60° could be detected. Lang [Lang 1983] developed a program to optimize the constellation parameters for minimum revisit times. A 15-minute revisit time was considered satisfactory. No single constellation was best for all requirements, but several alternatives with good coverage characteristics were identified. The choice depends on the range of latitudes of greatest interest. Lang also provided examples of coverage during constellation build-up.

Brousseau [Brousseau 1983 a] [Brousseau 1983 b] presented some of the mathematical considerations in simulating SBR, and described APL programs to study revisit times. In particular, a method for describing barriers or surveillance fences was described.

Rook [Rook 1983] [Rook et al. 1985] described the development of software to model SBR coverage and detection. This software formed the basis for the studies reported here, but has been extensively modified to improve graphical output, and to improve the fidelity of the radar models. For the studies reported here, however, the radar models were not used.

Rook [Rook 1983] discussed the number of satellites required to provide continuous coverage for circular, polar constellations at different altitudes, under the assumption that the field of view is an annulus on the surface of the earth lying between grazing angle limits of 5° and 60°. The coverage described is continuous in the orbital plane only. Rook [1983] also presented plots of coverage as a function of latitude for some representative circular and elliptical orbits.

Rook et al. [Rook et al. 1985] then described simulations of detection performance of a large SBR satellite in a low polar orbit. The effects of ground clutter were modelled, and the radar was assumed to use pulse-Doppler signal processing. Variation in detection performance with look angle for different latitudes was illustrated.

Slinn et al. [Slinn et al. 1986] described a simulation program for SBR that used a more accurate orbital model which included the effects of perturbations in the gravitational field and atmospheric drag. Methods for calculating satellite swaths and target motion were also described.

Saper [Saper 1988] provided a thorough review of the models developed by Brousseau, Rook, and Slinn, plus other more detailed SBR models not used for coverage studies.

Desmier [Desmier 1988 a] [Desmier 1988 b] used a geometrical model to study coverage available with SBR. Coverage was modelled as strips or swaths of a given width at different inclinations for various numbers of orbital planes. The results were plotted as the latitude above which coverage was maximum. Desmier concluded that for a swath width of 1000 nmi (1852 km) and four orbital planes, the inclination should be 85° to cover the pole.

Method

The model used for these coverage studies assumes a constellation of satellites in circular low-earth orbits. The orbits are defined using the Kepler equation, and assume that the earth is spherical.

Different constellations were defined by specifying the number of satellites in the constellation (from one to ten) and the number of orbital planes in which the satellites were distributed (Table 1). The other important constellation parameters were the altitude and inclination of the orbits. The altitudes chosen ranged from 1,000 to 6,000 km in steps of 1,000 km. For each of these altitudes, the inclinations ranged from 50° to 90° in steps of 10°. The longitude of the ascending node of the first satellite was required by the program. This was irrelevant and was always taken to be 0°. These constellations follow the Walker formalism [Walker 1977] for even distribution of satellites. This method of describing constellations is also described by Lang [Lang 1982] [Lang 1983]. An example of one of the constellations modelled is shown in Figure 1.

Table 1: Combinations of numbers of satellites and orbital planes used.

Number of satellites	1	2	3	4	5	6	7	8	9	10
Number of orbital planes	1	2	3	4	5	3	7	4	3	5

The field of view of the satellite was modelled as a moving annulus defined by grazing angle limits of 3° and 50° (Figure 2). Whenever a target fell within this annular region, it was considered to be visible. This means that there would be an opportunity for detection by the SBR satellite, but the success of such a detection would depend on many factors not considered in this coverage study.

Targets were placed at latitudes 10°, 40°, 60°, 70°, 80°, and 90°, and at a longitude of 100°W. (The longitude is irrelevant as long as the simulation is allowed to run long enough to cover the entire earth's surface several times. Any longitudinal dependence is then smoothed.) The targets were considered to be stationary. This permitted an examination of coverage as a function of latitude.

The simulation was allowed to run for a simulated time of four days. Opportunities for detection were evaluated every 10s of simulated time. The percentage of time that each target was visible by one or more satellites in the constellation was recorded. This is called *per cent visibility* in the plots that follow. Also the durations of the periods when targets were not visible to any satellite were recorded. These periods are referred to as coverage gaps.

The program used for these studies, *SBR2MD*, is documented in reports by Rook et al [Rook et al. 1985] and by Friend et al. [Friend et al. 1989], and in a *User's Guide* by Friend and Saper [Friend & Saper 1989].

Results

The results of the simulations were plotted in three ways:

- per cent visibility as a function of latitude for different altitudes at a given inclination
- per cent visibility as a function of latitude for different inclinations at a given altitude
- per cent visibility as a function of altitude for different inclinations at a given latitude

Examples of all three types of plots follow, for different numbers of satellites.

Figure 3 illustrates the coverage at different latitudes for one satellite in an orbit with 90° inclination and altitudes ranging from 1,000 to 6,000 km. For the lowest altitude, the coverage is best at 80° latitude but only reaches about 14%. For higher altitudes, coverage improves to a maximum of 25%, but the latitude of best coverage shifts down to 60°. That the coverage is better south of the pole for polar orbits can be explained by the presence of the nadir hole, the region between grazing angles of 50° and 90° where targets would not be visible to SBR. Satellites in polar orbits spend time directly over the pole, but this region is excluded from view. As the altitude increases the area of the nadir hole increases (compare Figures 4a & 4b), and the area of the annulus grows less rapidly with altitude (Figure 5). Coverage increases with altitude, but eventually levels off. This effect can be seen in Figure 3 for the two highest altitudes, where it is apparent that increasing altitude has led to diminishing returns in coverage.

Coverage gaps increased with decreasing latitude for all altitudes. The minimum gap was determined by the time that the target was in the nadir hole. Otherwise gaps were typically about one or more orbital periods in duration. Table 2 lists the orbital periods for each of the altitudes studied, and Figure 6 shows the maximum time that a target would be in the nadir hole as a function of satellite altitude. For a target at 80° latitude and a satellite at 1000 km altitude, the maximum gap was 91 min, and the average gap was 63 min. For a target at 60° latitude with a satellite at 6000 km altitude, the maximum gap was 179 min and the average gap was 116 min. Table 3 provides gap times for the cases with satellites at 1000 and 6000 km altitude. A jump in maximum gap times is shown between 70° and 60° for the satellite at 1000 km altitude, and between 40° and 10° for the satellite at 6000 km altitude.

Table 2: Orbital periods for circular orbits

altitude (km)	1000	2000	3000	4000	5000	6000
period (min)	105	127	150	175	201	228

Table 3: Coverage gap times for one satellite in polar orbit

Satellite Altitude (km)	Target Latitude (°)	Minimum Gap (min)	Maximum Gap (min)	Average Gap (min)	Gap Variance (min^2)
1000	90	3.50	89.33	46.02	30.76
1000	80	0.67	91.33	62.93	27.19
1000	70	0.50	96.33	74.19	20.98
1000	60	2.17	318.17	104.87	113.65
1000	40	2.33	588.00	189.32	662.85
1000	10	1.00	673.50	250.43	1252.75
6000	90	26.17	157.33	91.76	73.08
6000	80	22.50	162.50	91.19	75.36
6000	70	6.67	169.50	88.53	85.04
6000	60	16.67	179.17	115.80	74.30
6000	40	17.33	212.67	141.81	64.80
6000	10	15.83	519.00	198.95	404.76

For comparison with the polar orbit, Figure 7 shows the coverage for one satellite in an orbit having 50° inclination. The 1,000 km orbit provides no coverage for latitudes above 80° and only 6% visibility at 40° latitude. For a target at this latitude the maximum gap time was 798 min (13.3 hr). This corresponds to 7.6 orbital periods. The best coverage in the polar region is given by the 6000-km orbit, which reaches a maximum of 25% visibility. The gap time was always 173 min. Since the orbital period was 228 min, this shows that the target was observed on every orbit. These results illustrate the maxim that low-altitude orbits must have high inclinations to provide useful arctic coverage, and that there is a trade-off between altitude and inclination. Figure 8 reinforces this point by comparing coverage for different inclinations for the low-altitude satellite. It can be seen that for useful coverage at high latitudes, an orbit with inclination of 80° or greater should be chosen. In that case the target would be viewed every 90 min. Figure 9 compares the performance of the different orbits for a target at the pole. The best coverage for the polar target is obtained for a

satellite at an altitude of 5,000 km and 70° inclination. For this case the polar target would be viewed every 145 min. For a satellite in an orbit of 6000 km altitude and 60° inclination the target would be viewed every 174 min.

Adding a second satellite in an orthogonal orbit and delayed 180° with respect to the first effectively doubles the coverage, as can be seen by comparing Figure 10 with Figure 3. With only two satellites there is no overlapping coverage for any of the constellations chosen. Table 4 shows a reduction in the maximum gap times by one half to one third.

Table 4: Coverage gap times for two satellites in polar orbits

Satellite Altitude (km)	Target Latitude (°)	Minimum Gap (min)	Maximum Gap (min)	Average Gap (min)	Gap Variance (min^2)
1000	90	3.50	36.67	20.05	4.55
1000	80	0.33	41.50	26.77	4.29
1000	70	0.50	47.50	32.39	3.74
1000	60	0.33	91.50	48.65	14.60
1000	40	2.00	248.00	101.24	56.60
1000	10	1.00	305.83	131.93	143.23
6000	90	26.17	43.17	34.66	1.20
6000	80	22.33	53.33	34.07	1.85
6000	70	6.33	64.83	31.38	4.75
6000	60	3.33	77.33	38.03	7.04
6000	40	1.83	105.33	48.14	18.95
6000	10	5.67	186.00	99.32	74.53

Figure 11 shows the coverage for the two-satellite constellations when the target is at 80° latitude. At the lowest altitude, the 90°-inclination orbit provides the best coverage at 27%. Slightly better coverage can be obtained if the altitude is increased to 2,000 km and the inclination is decreased to 80° or 70°. The best coverage, 55%, is obtained at 6,000 km altitude and 60° inclination. Table 5 shows the coverage gaps for these cases. At 2000 km altitude, increasing the inclination from 70° to 80° buys shorter gap times. The increased coverage of higher altitudes comes at the expense of increased gap times.

Table 5: Coverage gap times at 80° latitude for 2 satellites

altitude (km)	inclination (°)	minimum gap (min)	maximum gap (min)	average gap (min)	gap variance (min^2)
1000	90	0.37	41.50	26.77	4.29
2000	80	1.67	44.50	27.64	3.95
2000	70	0.33	50.00	37.15	2.82
6000	60	1.67	66.83	46.00	4.98

When a third satellite is added to the constellation, the increase in coverage for the higher-altitude orbits is no longer linear for the highest altitudes. This can be seen by comparing Figure 12 with Figure 10. Overlaps in coverage have begun. However, there is still a substantial benefit in reduced gap times as shown in Table 6. Overlaps should also improve aggregate detection probabilities, but an estimate of that effect requires a simulation of radar performance as well as coverage. This is reserved for a later study.

Table 6: Coverage gap times for three satellites in polar orbits

Satellite Altitude (km)	Target Latitude (°)	Minimum Gap (min)	Maximum Gap (min)	Average Gap (min)	Gap Variance (min^2)
1000	90	3.50	19.17	11.35	1.00
1000	80	0.33	24.50	14.38	1.18
1000	70	0.50	30.50	17.80	1.64
1000	60	1.83	73.00	30.91	8.85
1000	40	0.17	98.00	66.99	20.13
1000	10	1.00	183.17	84.66	39.16
6000	90	5.00	26.33	15.56	1.88
6000	80	0.83	26.33	18.81	1.05
6000	70	0.33	28.67	17.74	1.04
6000	60	4.00	41.33	24.03	1.81
6000	40	2.67	68.00	38.27	10.53
6000	10	2.67	135.17	74.69	42.07

Figure 13 shows continuous coverage at latitudes above 80° for four-satellite constellations with inclination 60° at either 5,000 or 6,000 km altitude. Figure 14 demonstrates that a constellation of four satellites in orbits with 70° inclination achieve 100% coverage at the pole for altitudes of 4,000 or 5,000 km.

Once near continuous coverage is achieved for the high latitudes, adding satellites improves the coverage at lower latitudes. This is demonstrated by comparing Figure 15, showing five satellites in 60°-inclination orbits, with Figure 13. It can also be seen from Figure 15 that continuous coverage at the pole is now available with the 4,000-km orbit. As the number of satellites is increased, the advantage of going to higher altitudes decreases, because there is more overlap. Also, the maximum gap times for higher altitude constellations tend to be worse for targets at higher latitudes. This occurs when the maximum gap time is set by the time that the target is in the nadir hole. For an altitude of 6000 km this can be up to 27 minutes. Figure 16 shows that for a target at the pole, continuous coverage is obtained for a six-satellite constellation with altitude 2,000 km and inclination 70°.

Figure 17 shows that nearly continuous coverage at the pole is obtained at the lowest altitude considered, 1,000 km, with a constellation of seven satellites having an inclination of 80°. The coverage gaps for this constellation are shown in Table 7. For latitudes above 60° the maximum gaps are less then 20 min.

Table 7: Coverage gap times for 7 satellites at 1000 km altitude and inclination 80°

Target Latitude (°)	Minimum Gap (min)	Maximum Gap (min)	Average Gap (min)	Gap Variance (min)
90	0.17	0.17	0.17	0.00
80	0.17	3.83	1.42	0.02
70	0.50	19.17	4.07	0.19
60	0.67	17.67	7.09	0.33
40	1.33	58.50	19.53	6.91
10	0.17	77.83	41.01	22.69

Nearly continuous coverage at 10° latitude is achieved with eight satellites in orbits of altitude 6,000 km and inclination 50°, as shown in Figure 18. Figure 19 shows that coverage for this constellation is also good at high latitudes, but drops to just over 70% at mid latitudes. Table 8 lists the coverage gaps for this constellation.

Table 8: Coverage gap times for 8 satellites at 6000 km altitude and 50° inclination

Target Latitude (°)	Minimum Gap (min)	Maximum Gap (min)	Average Gap (min)	Gap Variance (min^2)
90	0.00	0.00	0.00	0.00
80	0.00	0.00	0.00	0.00
70	4.83	7.00	6.12	0.01
60	1.00	25.00	20.37	0.76
40	4.83	29.17	22.58	1.18
10	0.17	7.17	3.55	0.10

Good all-latitude coverage is obtained with nine satellites at 6,000 km altitude in three orbital planes of any inclination studied. As shown in Figure 20, the 90° inclination looks best. The maximum gap times are less than 15 min (10.83 min at 60° latitude) for targets above 40° latitude. The maximum gap at 10° latitude is 26 min and the average gap is 10.76 min.

For a final example, Figure 21 shows the results for constellations of ten satellites in five orbital planes of inclination 70° and different altitudes. This shows that increasing the altitude from 1,000 to 2,000 km buys significant extra coverage, especially at mid and low latitudes. If the primary interest is high latitudes, however, increasing altitude beyond 2,000 km might not be warranted. This is supported by Table 9, which shows that gap times improve appreciably when the altitude is increased from 1000 to 2000 km, but not much more if the altitude is further increased to 3000 km.

Table 9: Coverage gap times for 10 satellites at 70° inclination

Satellite Altitude (km)	Target Latitude (°)	Minimum Gap (min)	Maximum Gap (min)	Average Gap (min)	Gap Variance (min^2)
1000	90	0.00	0.00	0.00	0.00
1000	80	0.17	13.00	4.75	0.23
1000	70	0.67	8.50	2.95	0.07
1000	60	0.17	6.00	3.50	0.02
1000	40	0.17	34.17	20.72	1.61
1000	10	0.33	39.50	20.05	3.43
2000	90	0.00	0.00	0.00	0.00
2000	80	1.00	2.83	2.20	0.01
2000	70	2.33	7.83	6.78	0.03
2000	60	1.83	7.83	5.75	0.05
2000	40	0.17	11.17	7.34	0.20
2000	10	1.50	30.50	12.55	1.25
3000	90	0.00	0.00	0.00	0.00
3000	80	0.67	3.67	2.82	0.01
3000	70	3.00	11.00	8.28	0.09
3000	60	4.83	11.67	9.82	0.04
3000	40	0.17	6.17	4.45	0.05
3000	10	0.17	25.67	7.04	0.83

Discussion

These results describe opportunities for detection, not detection probabilities. Probabilities of detection would depend on the characteristics of the radar, the target, the clutter and other sources of interference, and the viewing geometry [Bird and Bridgewater 1984].

Furthermore these results assume that a target is in view if it lies in the annulus defined by limits in grazing angle of 3° and 50°. In fact an SBR would view only a portion of this area at any instant. In surveillance mode an SBR would likely scan near the lower grazing angle limit to take advantage of faster area sweep rates, lower clutter returns, and higher Doppler frequency shifts, and only scan to steeper grazing angles to track targets.

A more realistic coverage simulation might be to restrict the grazing angle to lie between 3° and 10°. This would reduce the percent visibility and could increase the maximum gap time, when the maximum gap time is set by the passage of the nadir hole. Overlapping coverage would then be more advantageous.

Overlaps in coverage could also be more advantageous when radar detection is considered, serving to increase the number of detections.

It has been assumed that coverage is independent of longitude. This assumption would fail for constellations in which the satellites all follow the same ground trace, or only a few ground traces that are synchronous with earth rotation [Lang 1983].

Despite these limitations, the results illustrate the trade-off between the altitude and inclination of the satellite constellation. For effective coverage of high latitudes, lower altitude constellations require orbits having higher inclinations, and more satellites. The best inclination for coverage of the pole is not a polar orbit, because of the effect of the nadir hole, which then passes directly over the pole.

Once continuous coverage is achieved at high latitudes, increasing the number of satellites improves coverage at lower latitudes. With increases in the number of satellites, the advantage of higher altitudes decreases.

Equivalent coverage can be obtained with different choices of number of satellites, altitude, and inclination of orbits. The choice would depend on the cost of each of the alternatives. Cost generally increases with each of those three factors. While higher altitude constellations can use fewer satellites, these satellites may have to be heavier and more expensive and the launch cost would be higher. Some choices might prove to be infeasible, if the launch requirements exceeded those available. Other factors influence the choice of altitude, including vulnerability to jamming and physical destruction.

Conclusion

Canada is primarily interested in radar coverage of its territory and surrounding regions, especially the Arctic. Good coverage at high latitudes could be achieved with a constellation of seven satellites in orbits of altitude 1000 km and inclination 80°. If the satellites were placed at a higher altitude, fewer satellites would be required, in lower inclination orbits.

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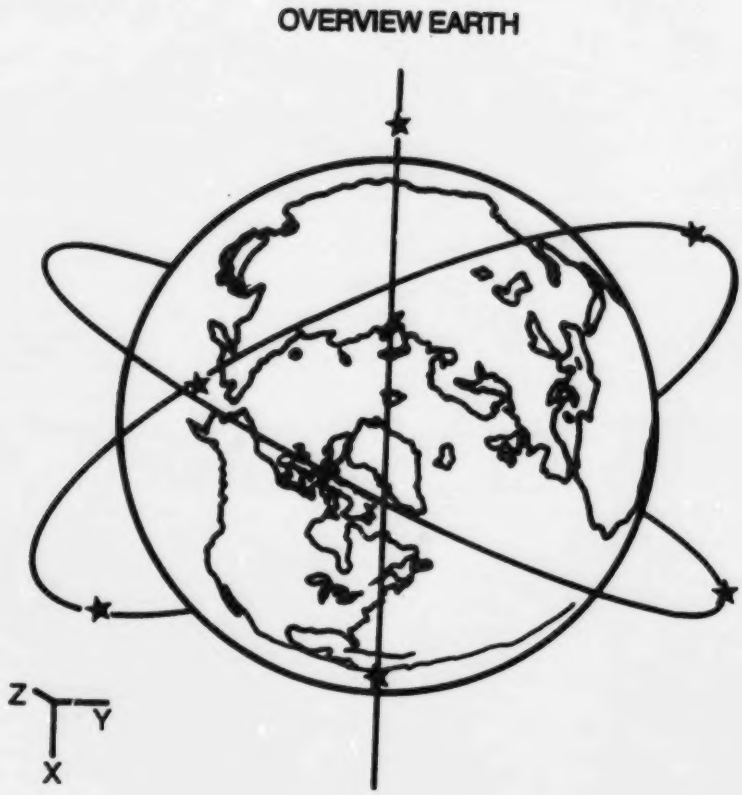

Figure 1. Example showing the orbits for six satellites at an altitude of 3000 km in three orbital planes with an inclination of 80°.

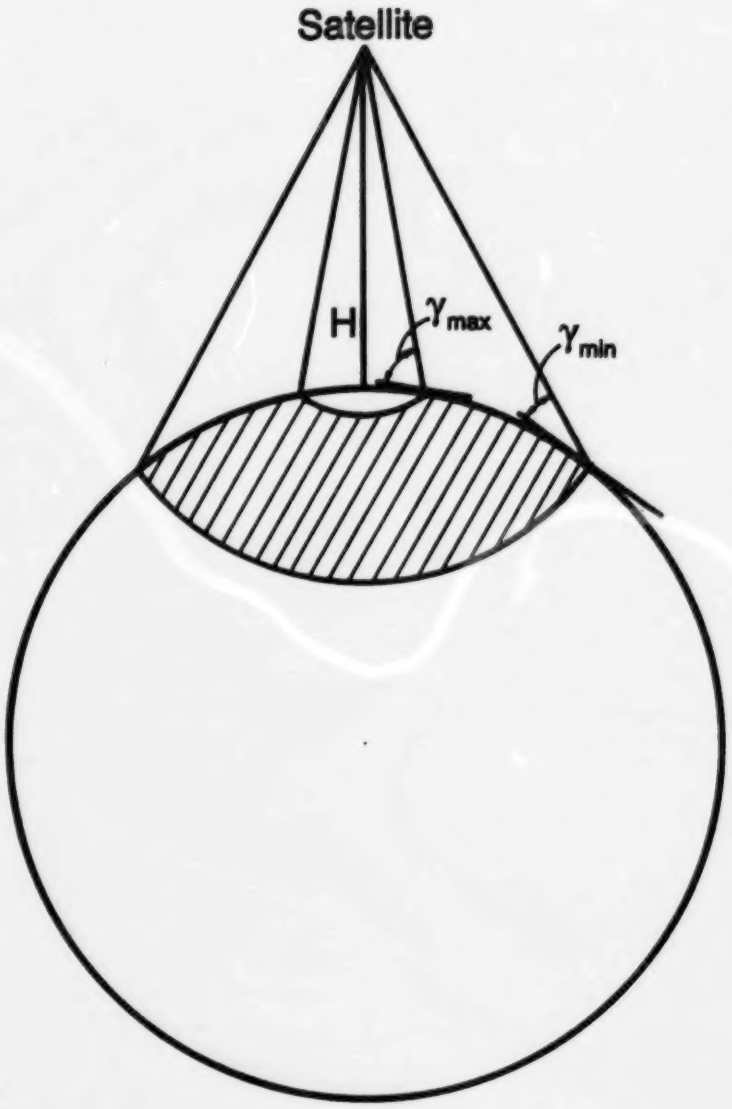

Figure 2. SBR coverage annulus defined by the grazing-angle limits, $\gamma_{min} = 3°$ and $\gamma_{max} = 50°$.

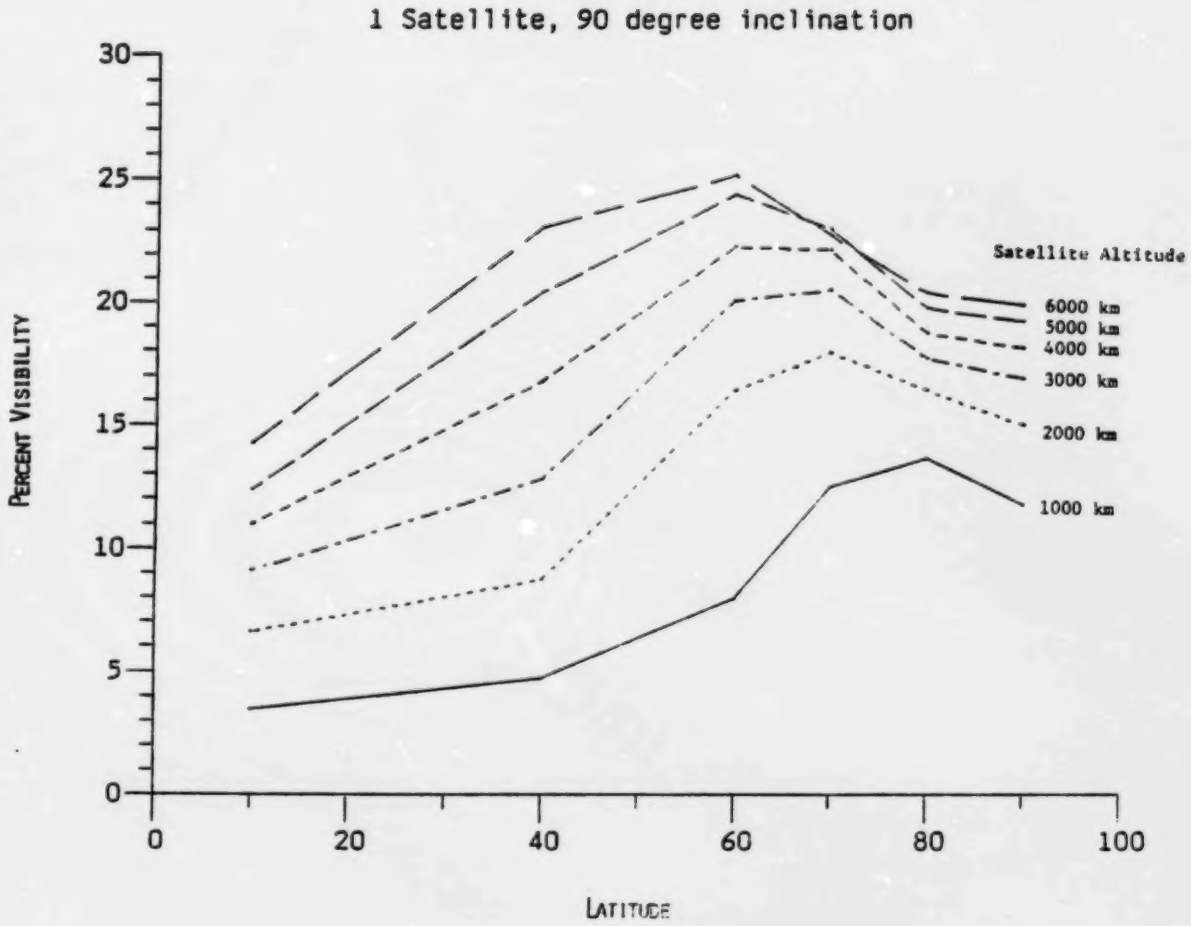

Figure 3. The coverage expressed as the percentage of time that a target could be viewed versus latitude, for one SBR satellite in a 90°-inclination orbit for satellite altitudes from 1000 to 6000 km.

Figure 4a. The coverage annulus for an SBR satellite at an altitude of 1000 km.

Figure 4b. The coverage annulus for an SBR satellite at 5000 km altitude. The area of the nadir hole increases as well as that of the annulus.

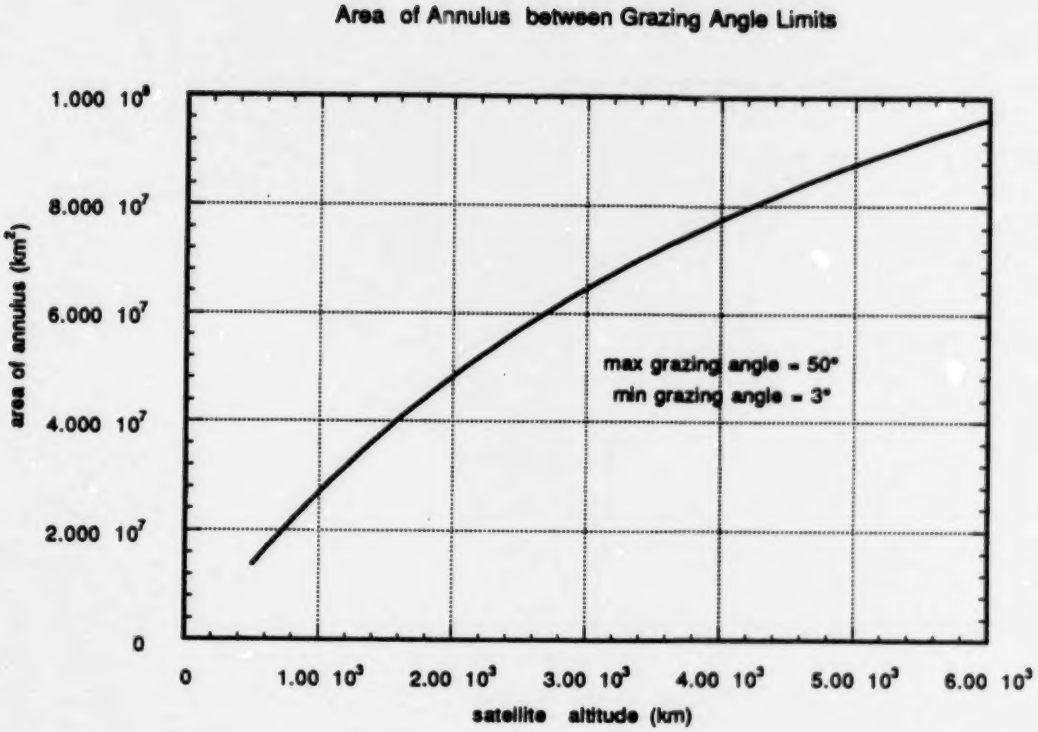

Figure 5. The area of the coverage annulus as a function of the altitude of the satellite.

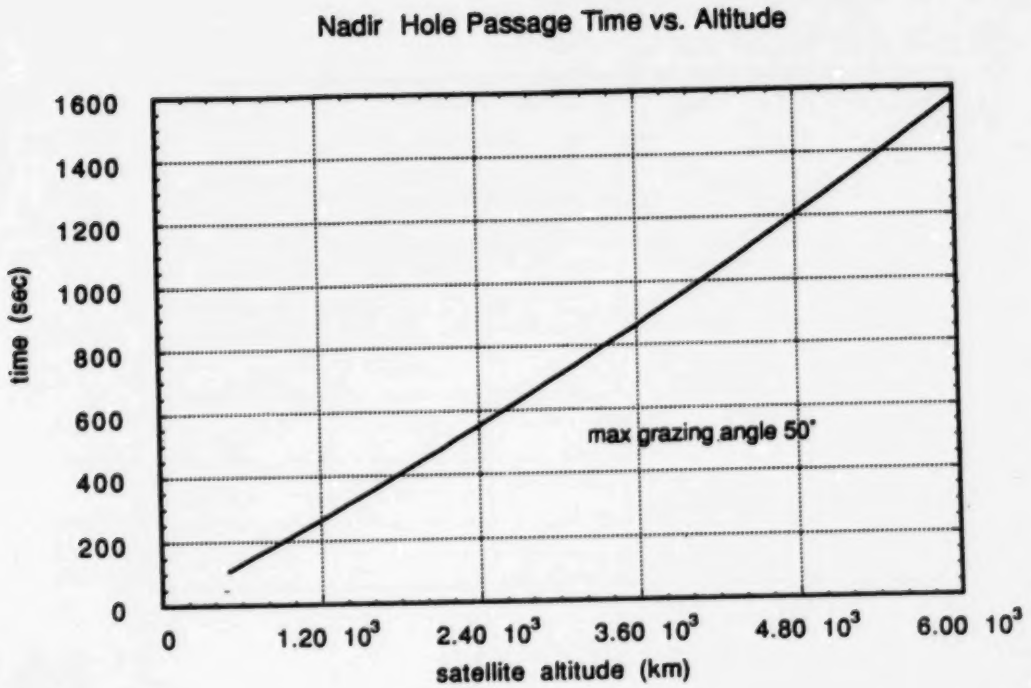

Figure 6. The maximum time that a target could be in the nadir hole as a function of the altitude of the satellite.

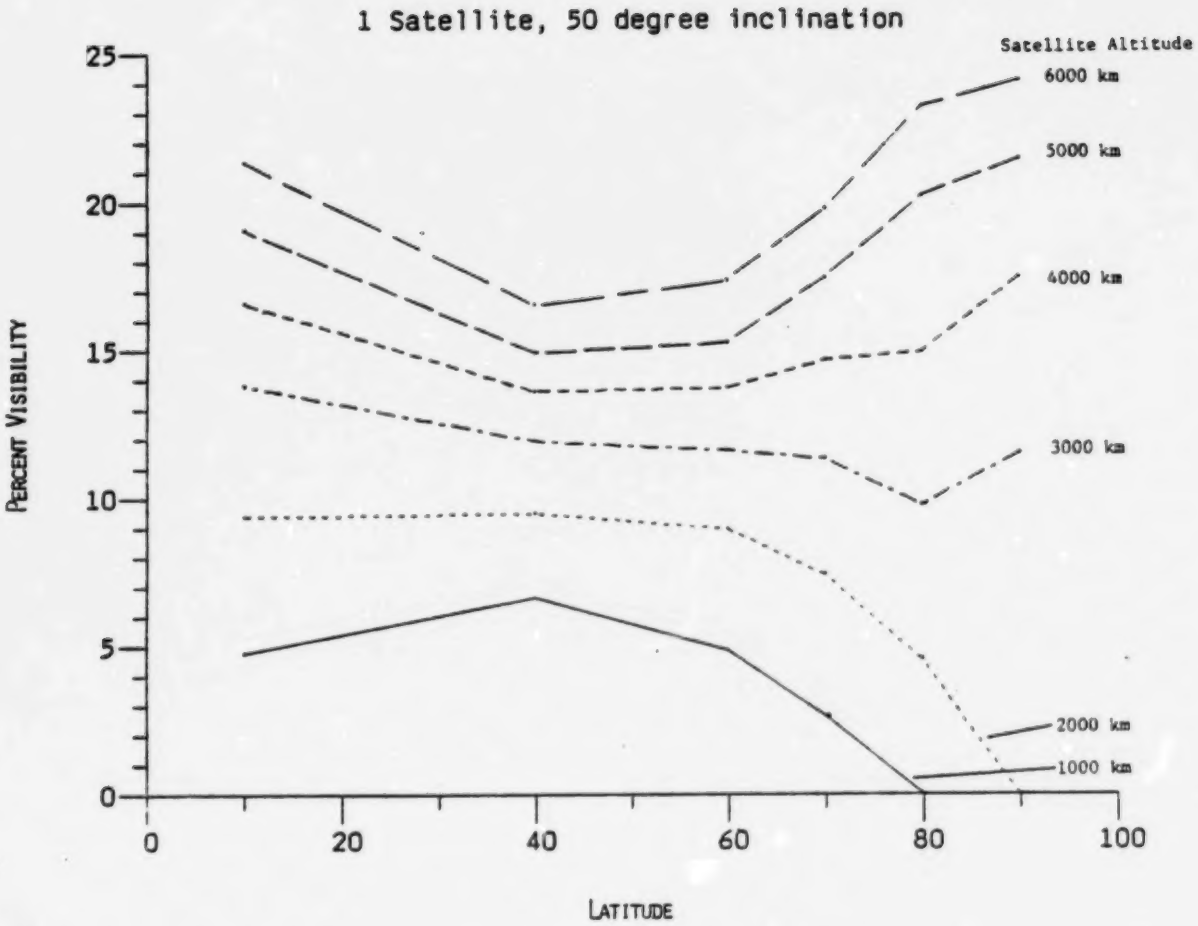

Figure 7. **Coverage as a function of latitude for one satellite in an orbit with 50° inclination, for various satellite altitudes.**

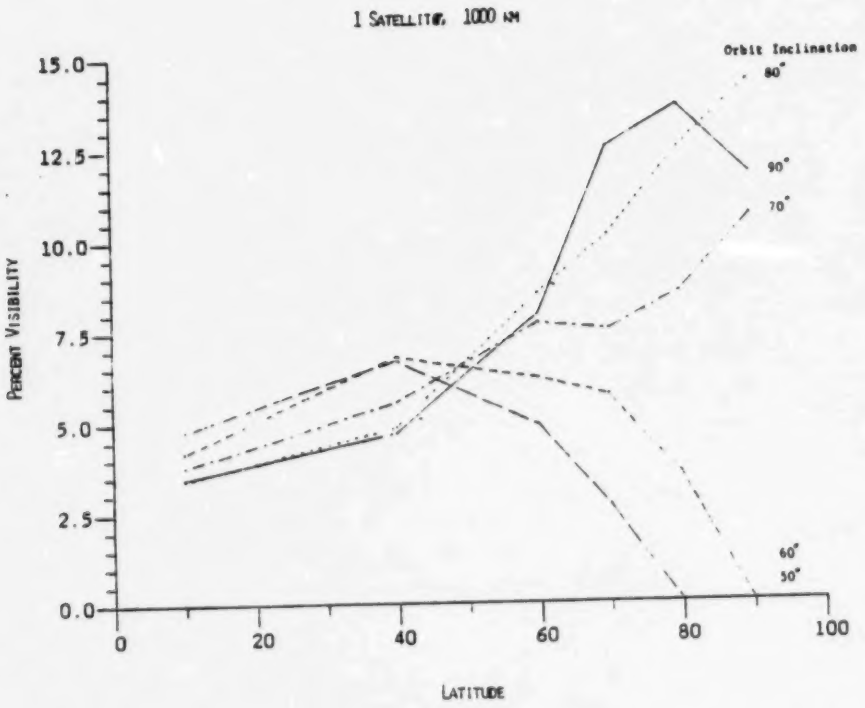

Figure 8. Coverage versus latitude for one satellite at altitude 1000 km.

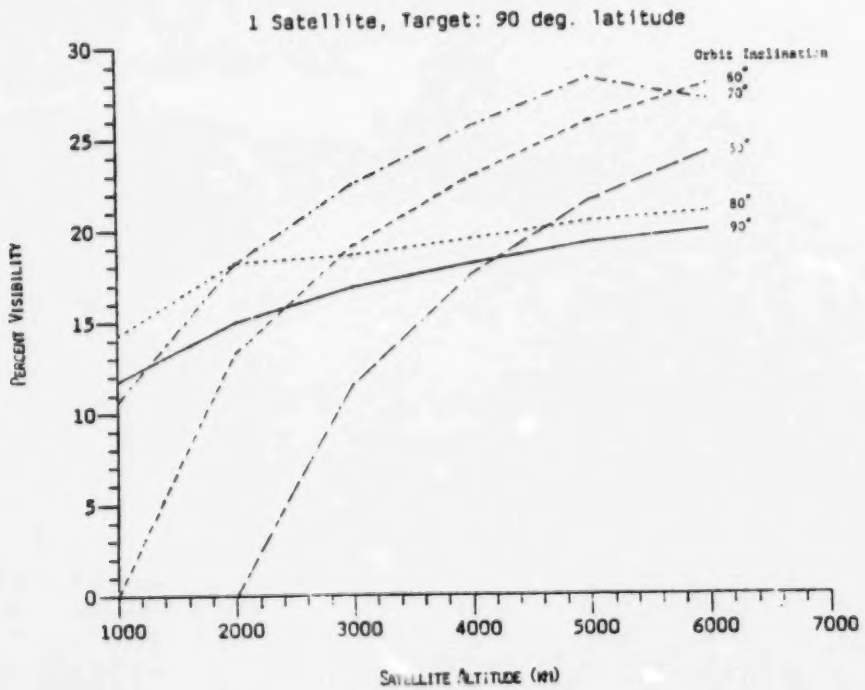

Figure 9. Coverage at the pole vs. altitude of one satellite in orbits of various inclinations.

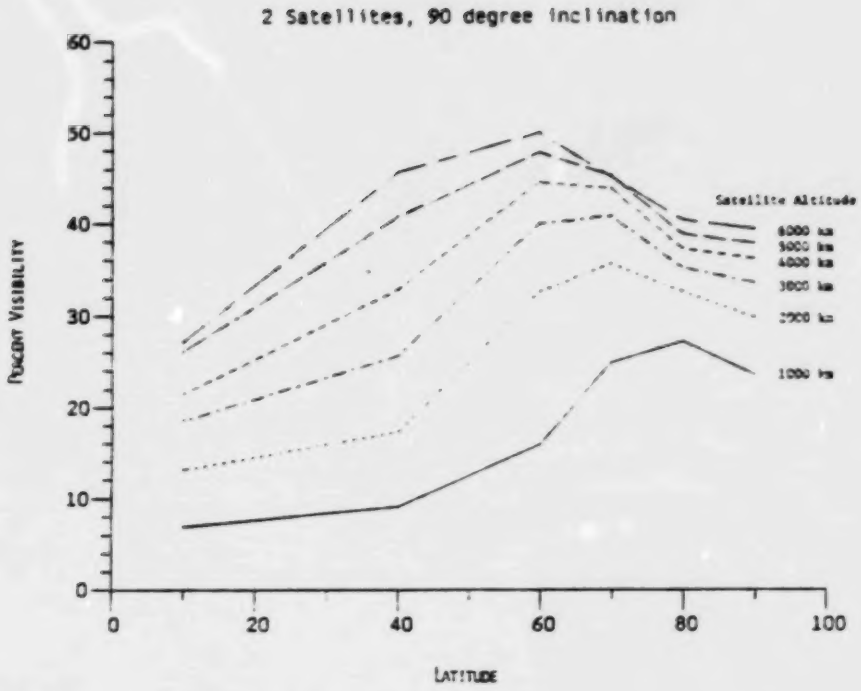

Figure 10. Coverage vs. latitude for two satellites in polar orbits.

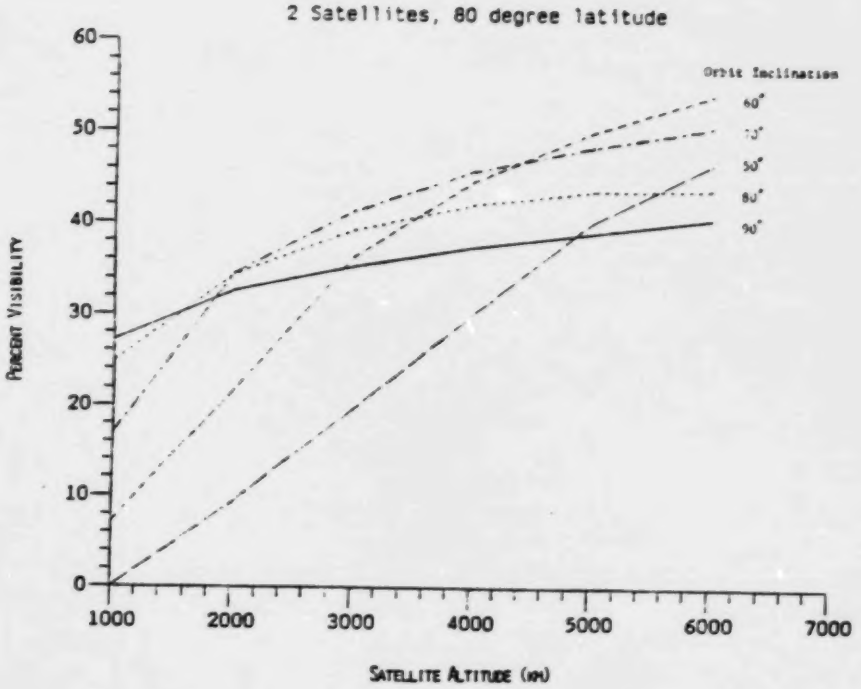

Figure 11. Coverage at 80° latitude vs. altitude for two satellites in orbits with various inclinations.

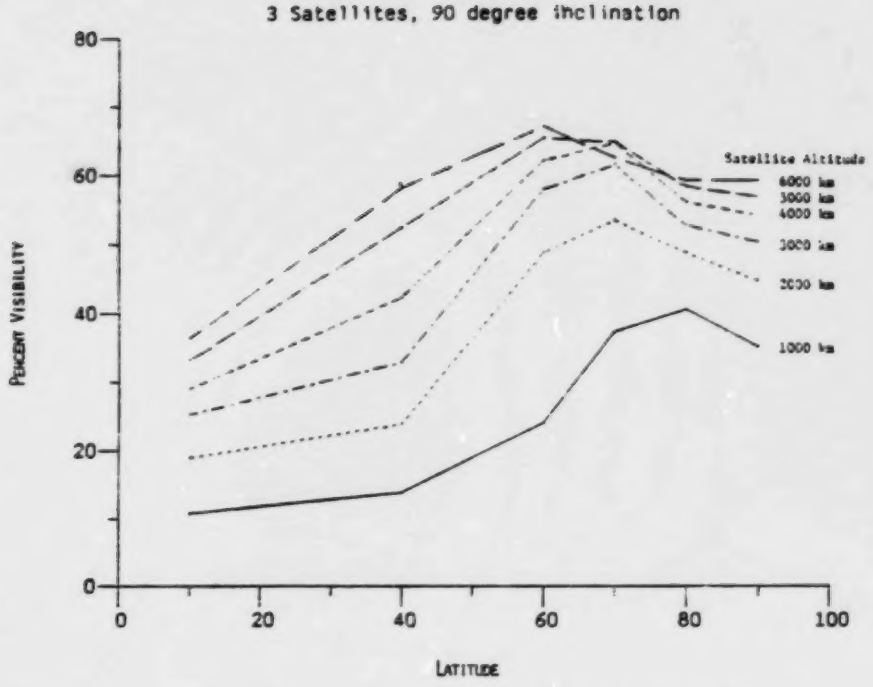

Figure 12. Coverage vs. latitude for three satellites in polar orbits.

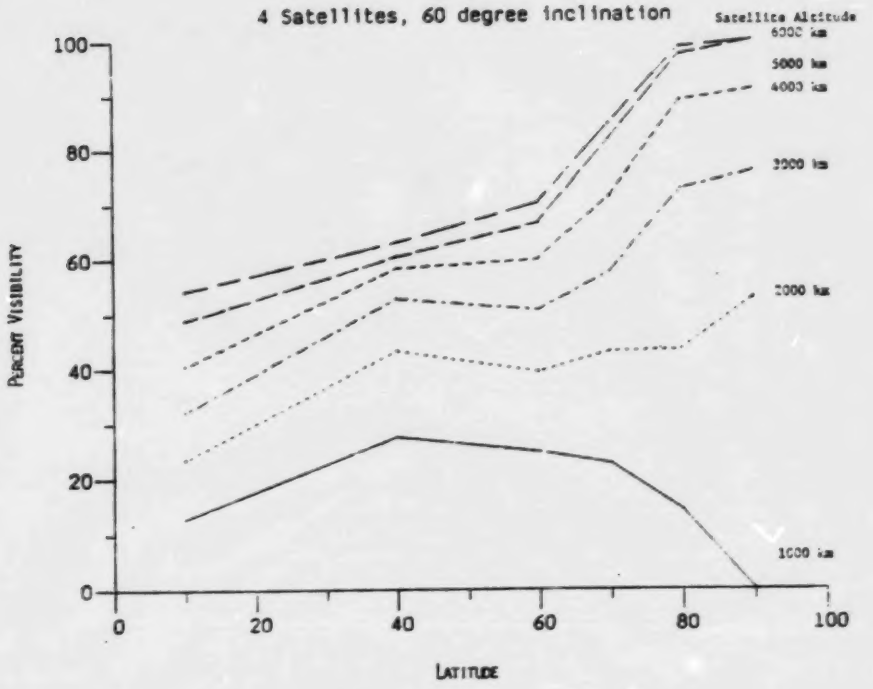

Figure 13. Coverage vs. latitude for four satellites in 60°-inclination orbits.

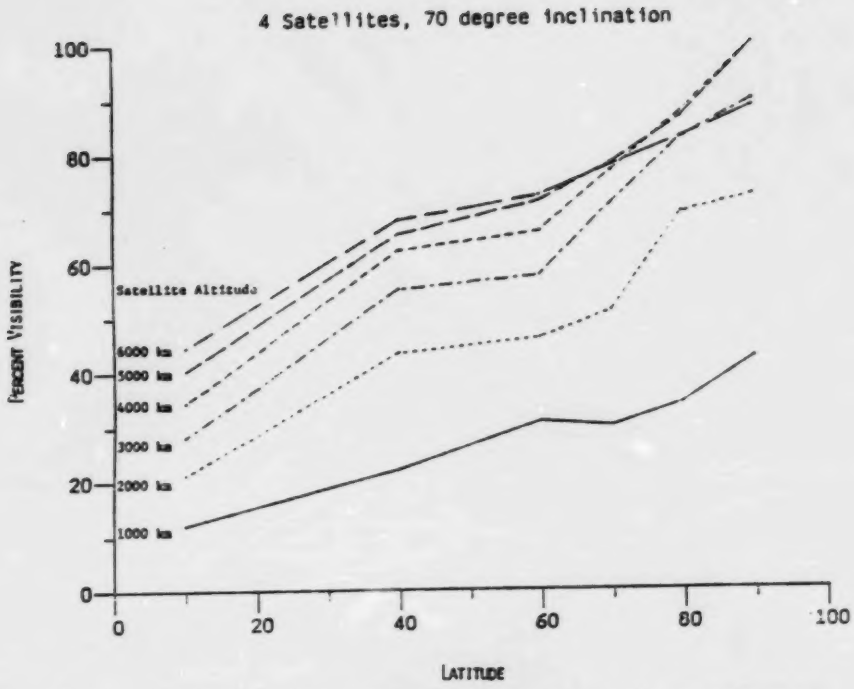

Figure 14. Coverage vs. latitude for four satellites in 70°-inclination orbits.

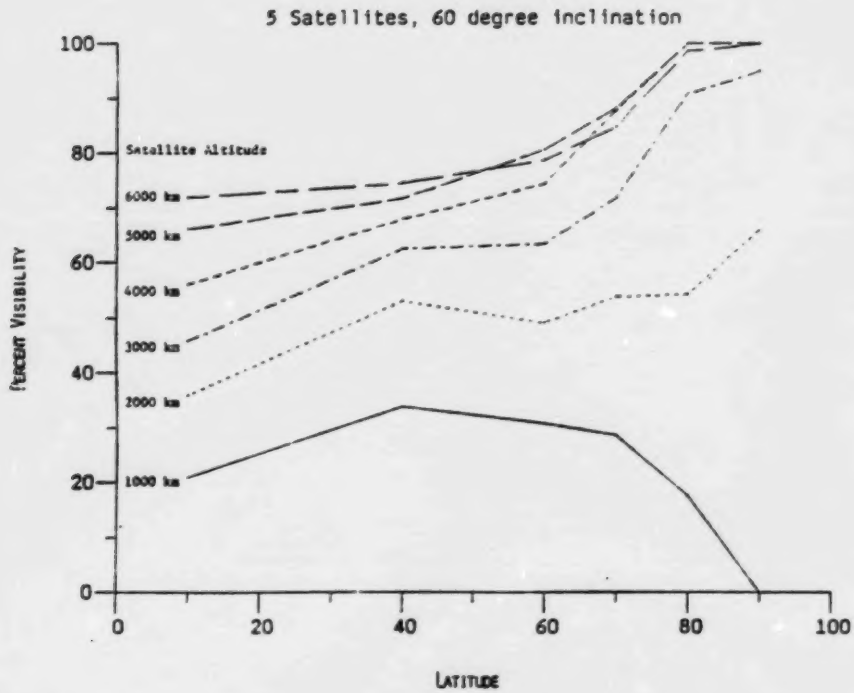

Figure 15. Coverage vs. latitude for five satellites in 60°-inclination orbits.

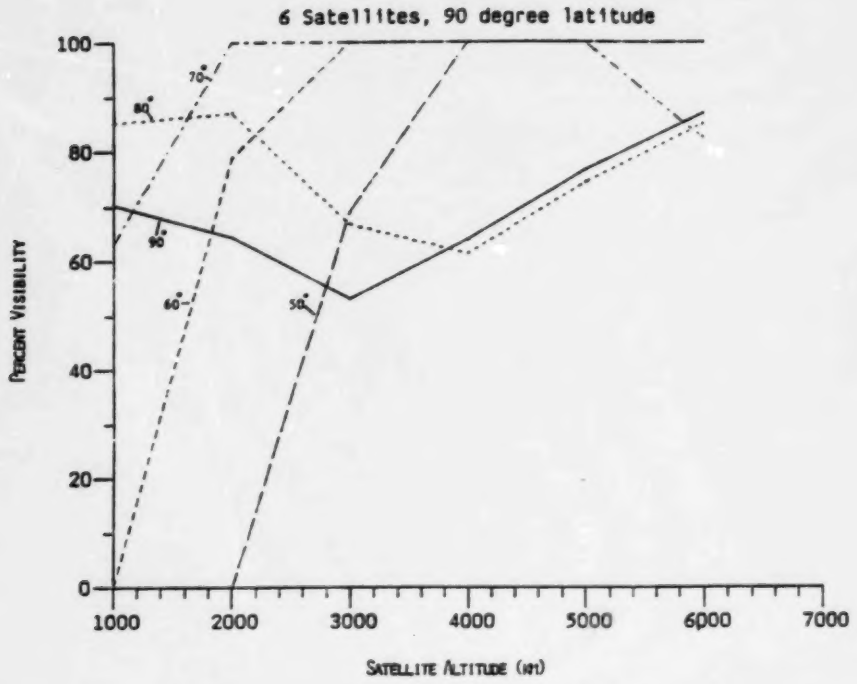

Figure 16. Coverage at the pole vs. satellite altitude for six satellites in orbits of various inclinations

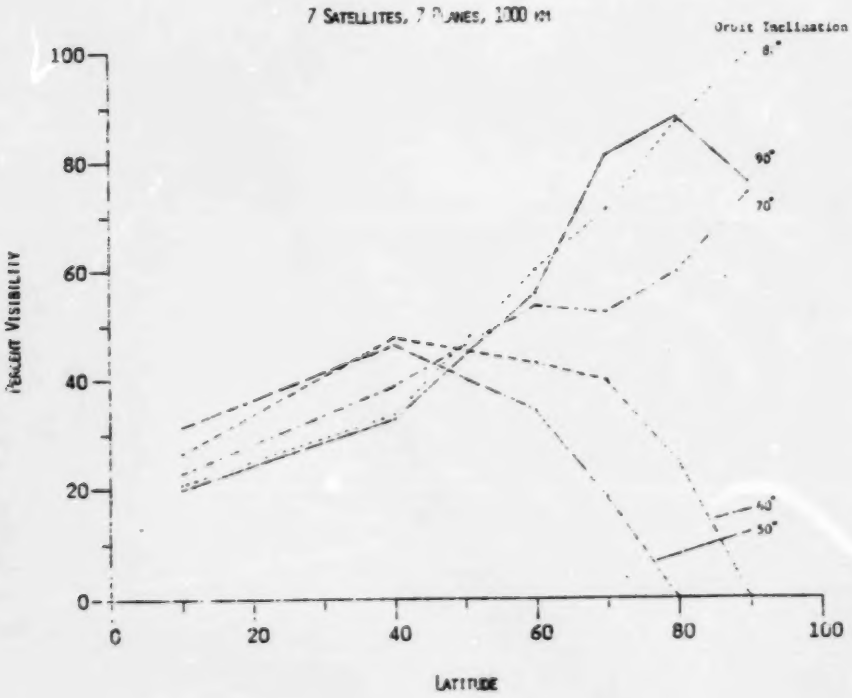

Figure 17. Coverage vs. latitude for seven satellites at 1000 km altitude.

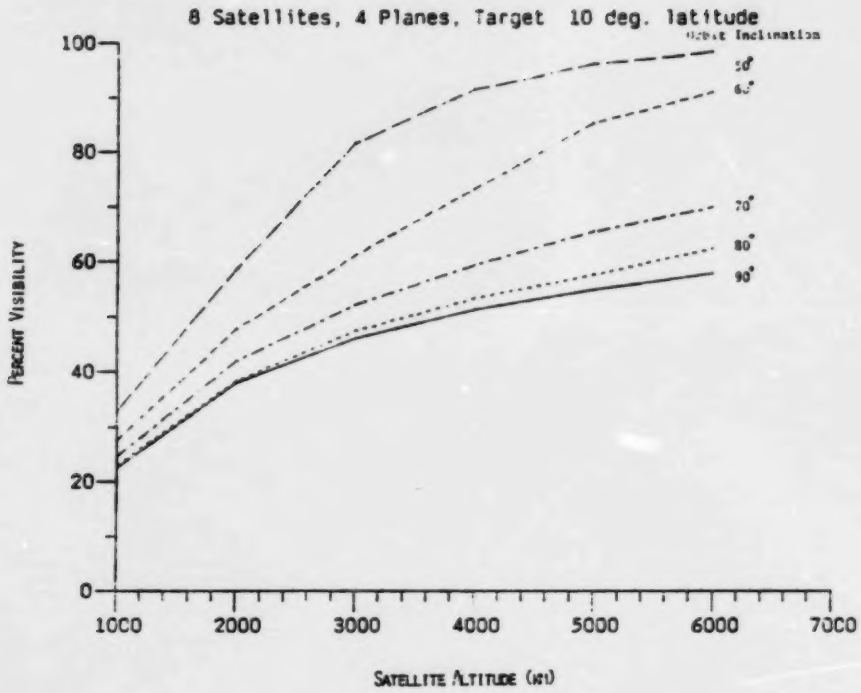

Figure 18. **Coverage at 10° latitude vs altitude for eight satellites in four orbital planes having various inclinations.**

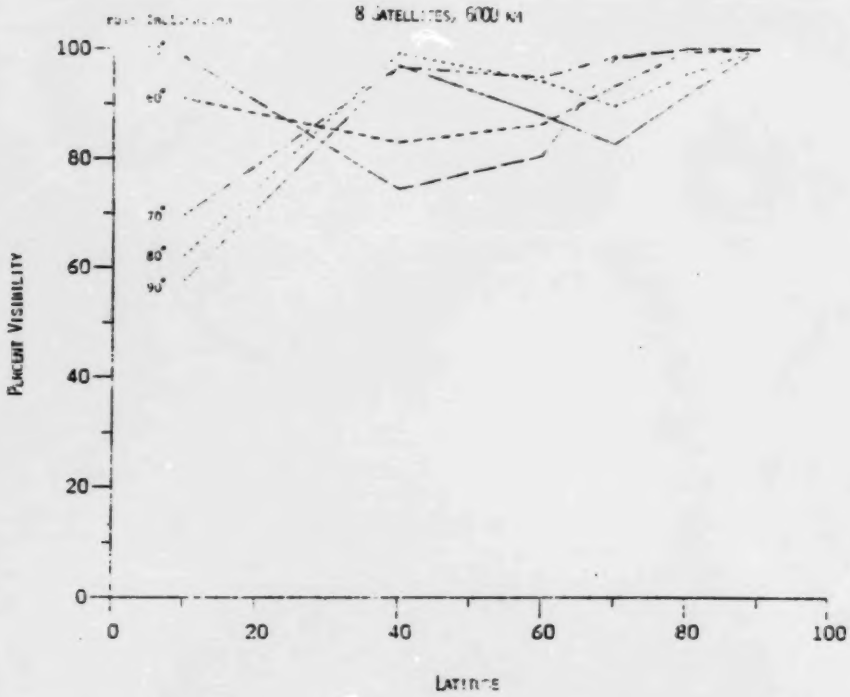

Figure 19. **Coverage vs. latitude for eight satellites at 6000 km altitude.**

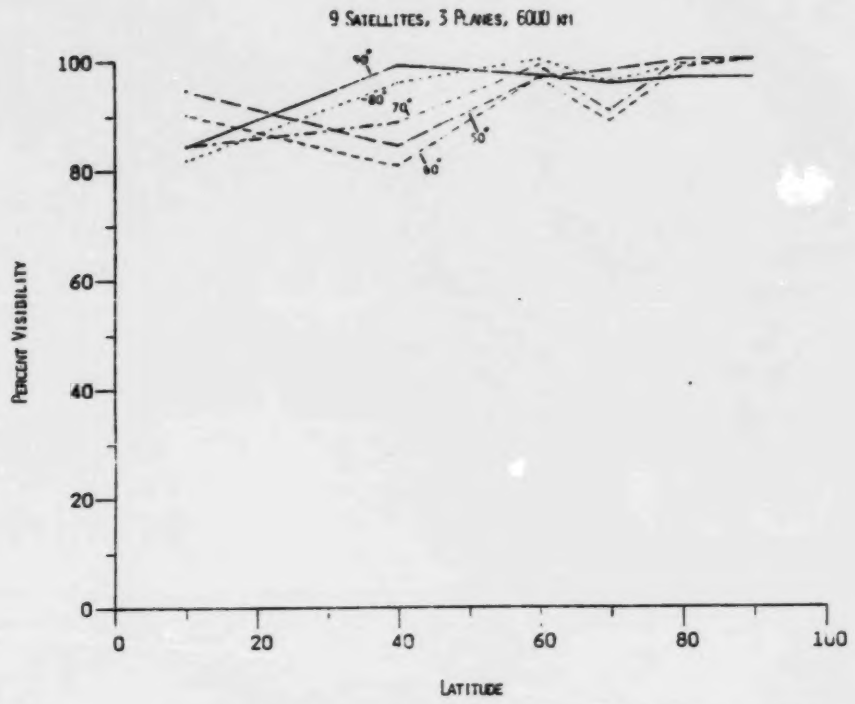

Figure 20. Coverage vs. latitude for nine satellites at an altitude of 6000 km.

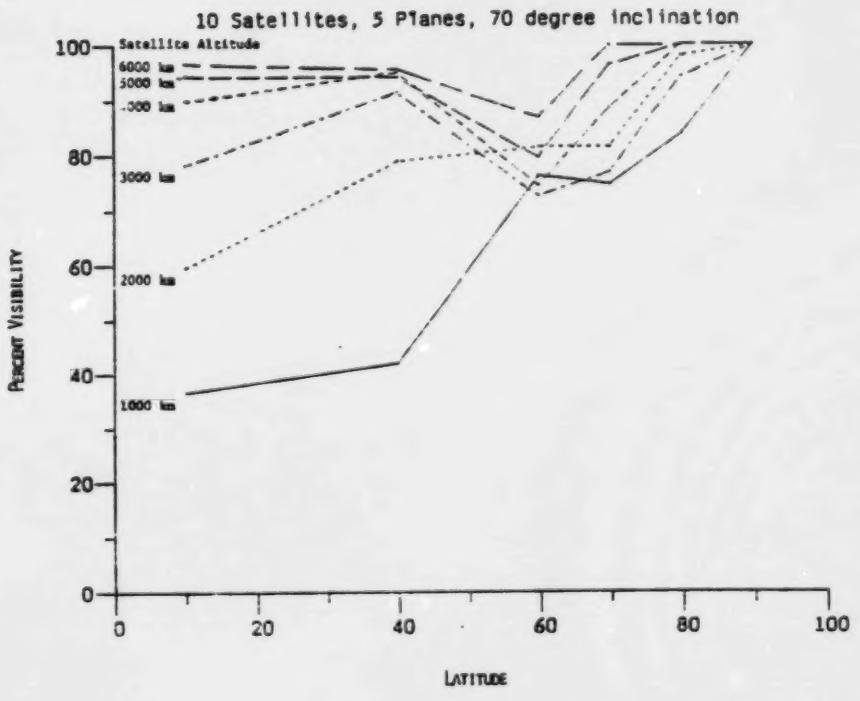

Figure 21. Coverage vs. latitude for ten satellites in five orbital planes with 70° inclination.

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3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

COVERAGE STUDIES FOR SPACE-BASED RADAR (U)

4. AUTHORS (Last name, first name, middle initial)

Maskell, Suzanne Y., and Eatock, Brian C.

5. DATE OF PUBLICATION (month and year of publication of document)

August 1990

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

28

6b. NO. OF REFS (total cited in document)

13

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Note

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

Defence Research Establishment Ottawa, Electronics Division,
Space-Based Radar

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

041LF

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10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

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The coverage for air surveillance available with constellation of space-based radar satellites was simulated. The coverage was modelled as an annulus, defined by the grazing-angle limits of 3°and 50°, moving over the earth. The number, altitude, and orbital inclination of the satellites were varied, and targets were placed at various latitudes. A constellation of seven satellites, at 1000 km altitude, and 80° inclination gave nearly continuous coverage at the pole. Equivalent coverage was obtained with fewer satellites at higher altitudes, and lower orbital inclination.

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